



Mechanical Characterization of Cryogenically Treated Aluminium–Copper Alloys through Experimental Investigations and Finite Element Analysis: A Comprehensive Review

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Abstract

Aluminium–copper (Al–Cu) alloys are widely used in aerospace, automotive, defence, and structural engineering applications because of their high specific strength, excellent machinability, and favourable strength-to-weight ratio. However, under rigorous service circumstances, wear, residual stresses, and microstructural instability frequently restrict their mechanical performance. Through grain refinement, precipitation strengthening, and residual stress reduction, deep cryogenic treatment (DCT) has become a successful post-processing method for enhancing the mechanical and tribological performance of Al–Cu alloys. The mechanical characterization of cryogenically treated Al–Cu alloys based on experimental studies and finite element analysis (FEA) is thoroughly reviewed in this work. The review critically investigates how microstructural evolution and mechanical properties are affected by cryogenic treatment factors such as cooling rate, soaking temperature, soaking duration, and post-aging. In addition to microstructural characterization using optical microscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD), experimental studies on hardness, tensile strength, yield strength, ductility, fatigue performance, wear resistance, and impact behavior are systematically analyzed. Recent developments in finite element analysis for predicting stress distribution, strain behavior, deformation characteristics, and residual stresses are reviewed, with an emphasis on the role of constitutive material models and experimental validation. Finite element analysis successfully predicts the mechanical response of cryogenically treated Al–Cu alloys while cutting development time and experimental expenses, according to a comparison of experimental results with numerical simulations. Multistate modeling, machine learning-assisted material optimization, digital twin technology, and integrated experimental–computational techniques for the design of high-performance Al–Cu alloys are only a few of the future prospects and research gaps identified by the review. For researchers and engineers working on cryogenic processing, mechanical

characterization, and computational modeling of advanced aluminum alloys, this review offers a thorough resource.

Keywords: Hardfacing, Deep Cryogenic Treatment, Finite Element Analysis

1. Introduction

Aluminum–copper (Al–Cu) alloys are among the most widely used precipitation-hardenable aluminum alloys in aerospace, automotive, defense, and structural engineering applications due to their high specific strength, excellent fatigue resistance, and favorable strength-to-weight ratio. Alloys such as AA2024, AA2014, AA2219, and AA2618 are frequently utilized in pressure vessels, aircraft construction, and transportation components where lightweight materials with superior mechanical performance are essential [1,5]. The long-term service performance of Al–Cu alloys is still affected by issues such as residual stresses, low wear resistance, and microstructural instability, despite the fact that artificial aging and conventional solution heat treatment significantly increase their strength. Consequently, researchers have focused on advanced post-processing techniques to enhance the mechanical properties and reliability of these alloys [3].

An efficient additional heat-treatment method that can enhance the mechanical and tribological performance of metallic materials is deep cryogenic treatment (DCT) [2, 6]. The procedure entails carefully freezing the material to cryogenic temperatures, immersing it for a lengthy time, gradually reheating it to ambient temperature, and then aging it as needed. According to a number of studies, cryogenic treatment improves hardness, tensile strength, fatigue life, and wear resistance by promoting grain refinement, precipitating fine strengthening phases, reducing residual stresses, and improving dimensional stability [4]. However, the published experimental results vary due to the considerable influence of alloy composition, cryogenic treatment parameters, and following heat-treatment conditions on the degree of increase [5].

Finite element analysis (FEA) has emerged as a key computational tool in recent years for forecasting engineering materials' mechanical behavior under various loading scenarios [7, 9]. While saving time and money compared to lengthy experimental investigations, numerical simulations offer important insights into stress distribution, strain localization, deformation properties, and residual stress evolution. There are still few thorough reviews that incorporate both experimental research and finite element analysis, despite the fact that numerous publications have separately reported the experimental characterization or numerical modeling of cryogenically treated Al–Cu alloys. Furthermore, there hasn't been enough attention paid to a rigorous assessment of the connections between cryogenic treatment parameters, mechanical properties, microstructural evolution, and computer modeling [8].

The major contributions of this review are summarized as follows:

- It provides a comprehensive review focused exclusively on cryogenically treated Al–Cu alloys, unlike previous reviews that broadly discuss cryogenic treatment of metallic materials.
- It critically correlates cryogenic treatment parameters with microstructural evolution and mechanical properties.
- It presents a comparative analysis of experimental investigations and finite element analysis for evaluating the mechanical behaviour of Al–Cu alloys.
- It identifies current research gaps in experimental methodologies, numerical modelling, and validation approaches.
- It outlines future research opportunities involving multistage simulation, artificial intelligence-assisted material design, and integrated experimental–computational approaches for advanced lightweight structural materials.

2. Aluminum–Copper Alloys

Aluminium–copper (Al–Cu) alloys, commonly designated as the 2xxx series aluminium alloys, are among the most important precipitation-hardenable alloys used in high-performance engineering applications. Their widespread utilization is primarily attributed to their excellent combination of high strength, low density, good machinability, and superior fatigue resistance. Copper serves as the principal alloying element, typically ranging from 2 to 6 wt.%, which significantly enhances mechanical strength through precipitation hardening. Depending on the alloy composition and heat-treatment condition, additional alloying elements such as magnesium, manganese, silicon, iron, zirconium, and titanium are incorporated to improve strength, corrosion resistance, thermal stability, and weldability. Representative alloys including AA2014, AA2024, AA2219, and AA2618 are extensively employed in aerospace structures, military vehicles, automotive components, railway systems, and pressure vessels where lightweight materials with excellent mechanical performance are essential[2,11].

Precipitation hardening, which includes solution heat treatment, quenching, and artificial aging, is primarily responsible for the exceptional mechanical characteristics of Al–Cu alloys. A series of precipitates, including equilibrium θ (Al_2Cu) phases, θ' , θ'' , and Guinier–Preston (GP) zones, occur inside the aluminum matrix as it ages. These widely distributed precipitates significantly increase hardness, yield strength, and tensile strength by efficiently preventing dislocation movement. On the other hand, extended aging or exposure to high temperatures can cause over-aging and precipitate coarsening, which reduces mechanical characteristics [4,10]. Furthermore, residual stresses created during production and service conditions can negatively impact wear resistance, fatigue life, and dimensional stability, which limits the overall performance of Al–Cu alloy components..

Many studies have concentrated on sophisticated post-processing methods such deep cryogenic treatment in order to get beyond these restrictions. Cryogenic processing has been shown to increase the mechanical and tribological performance of Al–Cu alloys, relieve residual stresses, refine the microstructure, and encourage the production of uniformly distributed strengthening precipitates. Alloy composition, soaking temperature, soaking time, chilling rate, and post-treatment aging circumstances all affect how successful cryogenic treatment is. Therefore, optimizing cryogenic treatment parameters and creating high-performance Al–Cu alloys for demanding engineering applications require an understanding of the link between alloy composition, microstructural evolution, and mechanical behavior. Figure 2 displays the binary phase diagram of aluminum and copper (Al–Cu).

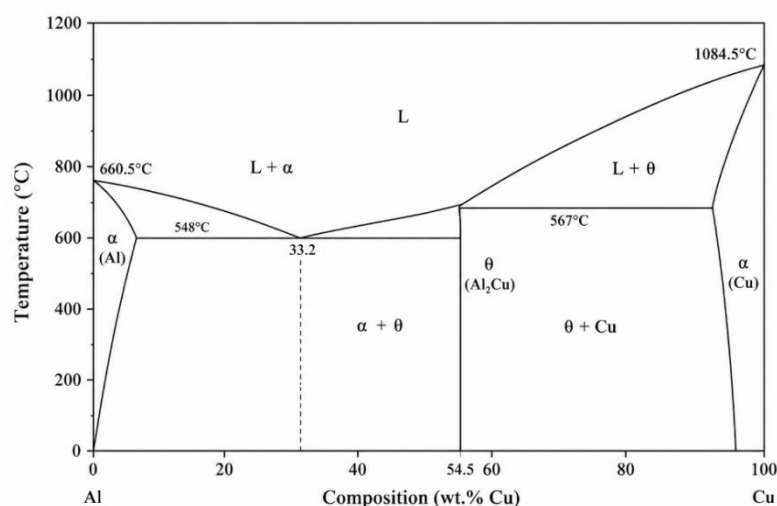


Fig.2. Aluminium–copper (Al–Cu) binary phase diagram

3. Fundamentals of Cryogenic Treatment

Cryogenic treatment is acknowledged as a sophisticated additional heat-treatment method used to enhance metallic materials' mechanical performance and microstructural stability. In contrast to traditional heat treatment, cryogenic processing entails subjecting materials to extremely low temperatures under carefully regulated circumstances, then gradually warming them and, if necessary, aging them afterwards. Because it may greatly increase a material's hardness, strength, fatigue life, wear resistance, and dimensional stability without changing its chemical makeup, the method has garnered a lot of attention. Cryogenic treatment improves the overall mechanical performance of aluminum–copper (Al–Cu) alloys by influencing precipitation kinetics, grain structure, and residual stress distribution. However, processing variables including chilling rate, cryogenic temperature, soaking time, and post-treatment aging have a significant impact on the treatment's efficacy.

3.1 Types of Cryogenic Treatment

Cryogenic treatment is generally classified into shallow cryogenic treatment (SCT) and deep cryogenic treatment (DCT) according to the minimum processing temperature. In SCT, materials are cooled to temperatures typically ranging between -80°C and -120°C , whereas DCT involves exposure to temperatures approaching that of liquid nitrogen (approximately -196°C). Although both processes contribute to stress relief and dimensional stability, DCT has been widely reported to produce superior improvements in mechanical and tribological properties because of its greater influence on microstructural evolution. For precipitation-hardenable Al–Cu alloys, deep cryogenic treatment promotes a more uniform distribution of strengthening precipitates, enhances grain refinement, and reduces residual stresses, resulting in improved hardness, tensile strength, and fatigue resistance. Consequently, DCT has become the preferred cryogenic processing technique for high-performance engineering applications.

3.2 Cryogenic Treatment Process

A typical cryogenic treatment cycle consists of controlled cooling, cryogenic soaking, gradual warming, and post-treatment aging. The material is initially cooled at a predetermined rate to minimize thermal gradients and avoid the development of thermal stresses. After reaching the desired cryogenic temperature, the material is maintained under isothermal conditions for several hours, allowing sufficient time for microstructural rearrangement and stress relaxation [12]. Following the soaking period, gradual warming to room temperature is carried out to prevent thermal shock and preserve dimensional stability. In many applications involving Al–Cu alloys, artificial aging is subsequently performed to accelerate precipitation hardening and maximize mechanical performance. The combination of cryogenic treatment and aging has been shown to produce finer precipitates and improved precipitation kinetics compared with conventional heat treatment alone. The typical cryogenic process flowchart shown in Fig 1.

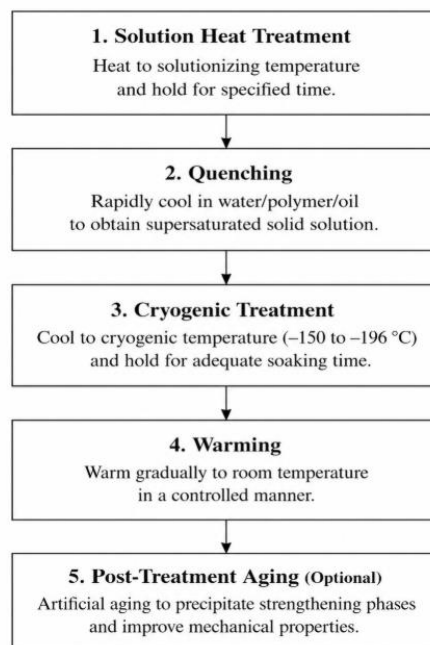


Fig1: The typical cryogenic process

3.3 Influence of Cryogenic Treatment Parameters

The improvement in mechanical properties achieved through cryogenic treatment is governed by several processing parameters. Among these, cryogenic temperature and soaking duration play the most significant roles in determining the extent of microstructural modification. Lower treatment temperatures generally promote greater residual stress relaxation and finer precipitation, while adequate soaking duration facilitates diffusion-controlled processes responsible for precipitate nucleation and stabilization. Similarly, controlled cooling and warming rates are essential for minimizing thermal stresses and ensuring uniform microstructural development throughout the material. The effectiveness of cryogenic treatment is further influenced by post-aging conditions, as appropriate aging promotes the formation of fine metastable precipitates that contribute to precipitation strengthening. Therefore, optimization of cryogenic processing parameters is essential to achieve the desired balance between strength, ductility, and wear resistance in Al–Cu alloys[3,14].

3.4 Mechanisms of Property Enhancement

The mechanical improvements observed after cryogenic treatment are primarily attributed to several interconnected microstructural mechanisms. Exposure to cryogenic temperatures promotes grain refinement and increases the density of grain boundaries, thereby restricting dislocation movement and enhancing strength according to the Hall–Petch relationship. Simultaneously, cryogenic processing accelerates the nucleation of fine precipitates during subsequent aging, leading to effective precipitation strengthening through the formation of GP zones and metastable Al_2Cu phases. Another important effect is the relaxation of residual stresses generated during casting, machining, and conventional heat treatment, which contributes to improved dimensional stability and fatigue performance [15]. Furthermore, the interaction between dislocations and uniformly distributed precipitates increases resistance to plastic deformation, resulting in higher hardness, tensile strength, and wear resistance. The combined influence of these mechanisms explains the superior mechanical performance of cryogenically treated Al–Cu alloys and provides the scientific basis for their increasing application in aerospace, automotive, and structural engineering components [4,17].

4. Experimental Characterization Techniques

Experimental characterization is essential for evaluating the influence of cryogenic treatment on the mechanical performance and microstructural evolution of aluminum–copper (Al–Cu) alloys. A combination of standardized mechanical testing and advanced microstructural characterization techniques is employed to establish the relationship between cryogenic processing parameters, microstructural changes, and material properties. Most investigations begin with solution heat treatment and quenching of the alloy, followed by deep cryogenic treatment (typically at -196°C) for varying soaking durations and, in some cases, subsequent artificial ageing. The treated specimens are then subjected to mechanical and metallurgical characterization according to relevant ASTM standards to ensure repeatability and reliability.

Mechanical characterization primarily includes tensile, hardness, impact, fatigue, and wear testing. Tensile testing, generally performed according to ASTM E8/E8M, determines the ultimate tensile strength, yield strength, Young's modulus, and elongation, providing insight into the strengthening effects induced by cryogenic treatment [11,20]. Vickers microhardness testing (ASTM E384) is widely used to evaluate surface hardness and precipitation strengthening, while Charpy impact testing (ASTM E23) assesses the toughness and energy absorption capacity of the treated alloys. Wear behavior is commonly investigated using a pin-on-disc tribometer in accordance with ASTM G99, where wear rate, friction coefficient, and material loss are measured under controlled loading and sliding conditions. Fatigue performance is evaluated using cyclic loading tests following ASTM E466, enabling the assessment of crack initiation, crack propagation, and fatigue life enhancement resulting from cryogenic processing.

Microstructural characterization complements mechanical testing by revealing the mechanisms responsible for property improvement. Optical microscopy (OM) is employed for grain structure observation, whereas Scanning Electron Microscopy (SEM) is extensively used to analyze fracture surfaces, wear tracks, and precipitate morphology. Transmission Electron Microscopy (TEM) provides high-resolution imaging of nanoscale precipitates and dislocation structures, while Energy Dispersive X-ray Spectroscopy (EDS) determines the elemental distribution within the microstructure. Electron Backscatter Diffraction (EBSD) is increasingly utilized to study grain orientation, crystallographic texture, and grain boundary evolution. Additionally, X-ray Diffraction (XRD) is used to identify phase constituents, evaluate residual stresses and analyses crystallite size and lattice strain after cryogenic treatment.

The integration of these experimental techniques enables a comprehensive understanding of the effects of cryogenic treatment on Al–Cu alloys. Numerous studies have reported improvements in hardness, tensile strength, wear resistance, and fatigue life, primarily attributed to grain refinement, increased dislocation density, precipitation of strengthening phases, and residual stress relaxation [12, 19]. Furthermore, the experimentally obtained material properties serve as essential input parameters for finite element analysis (FEA), facilitating the validation of numerical models and accurate prediction of the mechanical behavior of cryogenically treated components under service conditions. Consequently, experimental characterization forms the foundation for optimizing cryogenic processing parameters and advancing the application of Al–Cu alloys in aerospace, automotive, and other high-performance engineering sectors.

5. Correlation between Experimental and Numerical Results

The correlation between experimental investigations and finite element analysis (FEA) is crucial for accurately evaluating the mechanical behavior of cryogenically treated aluminum–copper (Al–Cu) alloys. Experimental techniques such as tensile, hardness, fatigue, and wear testing provide essential material properties, including yield strength, ultimate tensile strength, elastic modulus, and stress–strain behavior, which serve as input parameters for numerical simulations. Finite element models developed using software such as ANSYS, Abacus, and COMSOL Multiphysics predict stress distribution, strain localization, deformation, and failure behavior under various loading conditions. Comparison of simulated results with experimental observations enables validation of numerical models and improves confidence in predicting the performance of cryogenically treated components. Most reported studies demonstrate good agreement between experimental and numerical results, with prediction errors generally within 5–10%, indicating the reliability of finite element modeling for engineering applications [17, 16].

The combined use of experimental characterization and numerical simulation provides a comprehensive understanding of the strengthening mechanisms induced by cryogenic treatment, including grain refinement, precipitation hardening, and residual stress relaxation. While minor discrepancies between experimental and simulated results may arise due to simplified material models, idealized boundary conditions, and the exclusion of microstructural heterogeneity, finite element analysis effectively captures the overall deformation and failure behavior of Al–Cu alloys. This integrated approach significantly reduces experimental costs, shortens product development cycles, and enables optimization of cryogenic treatment parameters before component fabrication. Future studies should focus on incorporating microstructure-based constitutive models, crystal plasticity finite element methods, and machine learning-assisted simulations to enhance prediction accuracy and facilitate the design of lightweight, high-performance aluminum alloy components for aerospace, automotive, and defense applications [15, 16].

6. Conclusions

- Cryogenic treatment is an effective supplementary heat-treatment process for enhancing the mechanical performance of aluminum–copper (Al–Cu) alloys through grain refinement, precipitation strengthening, and residual stress relaxation.
- Experimental investigations consistently demonstrate improvements in hardness, tensile strength, wear resistance, fatigue life, and dimensional stability when optimized cryogenic processing parameters are employed.
- The mechanical performance of cryogenically treated Al–Cu alloys is strongly influenced by processing variables, including cooling rate, soaking temperature, soaking duration, warming rate, and subsequent ageing treatment.
- Advanced characterization techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), electron backscatter diffraction (EBSD), X-ray diffraction (XRD), and energy-dispersive spectroscopy (EDS) have provided significant insights into the microstructural evolution responsible for property enhancement.
- Finite element analysis (FEA) has emerged as a reliable numerical tool for predicting stress distribution, deformation behavior, strain localization, and failure characteristics, with good agreement reported between experimental observations and numerical simulations.
- The integration of experimental characterization and computational modeling provides an efficient framework for optimizing cryogenic treatment parameters, reducing experimental costs, and accelerating the design of lightweight, high-performance engineering components.

- Despite significant progress, further research is required to establish standardized cryogenic treatment protocols, develop microstructure-based constitutive models, and improve the prediction accuracy of finite element simulations.
- Future research should focus on integrating cryogenic treatment with advanced manufacturing technologies, additive manufacturing, artificial intelligence, machine learning, and multistage modeling to develop next-generation Al–Cu alloys for aerospace, automotive, defense, and other high-performance engineering applications.

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